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PARAMETER SENSITIVITY ANALYSIS OF TAILORED-PULSE-LOADING STIMULATION OF DEVONIAN GAS SHALE

Sub-task Technical Report
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EXECUTIVE SUMMARY

As part of Science Applications' involvement in the Eastern Gas Shales Project, a research program is being conducted to evaluate unconventional wellbore stimulation technologies. Included in this effort is the development of numerical models to describe and predict laboratory experiment and field demonstration results. The numerical model development is also being used in parameter sensitivity analyses to determine the importance of various aspects of dynamic wellbore loading phenomenology.

This report presents the results of a numerical evaluation of the tailored-pulse-loading concept in stimulating gas shale. Tailoring the pulse that the wellbore rock experiences has been attempted in a number of ways. Various explosives which detonate and propellants which deflagrate have been used alone or in combination to achieve the desired result. Decoupling the charge from the borehole wall by centering it in an open air-filled borehole or by using a liquid pad between the centered charge and the wellbore wall is also another approach to tailoring the pressure pulse which the rock experiences. Each has the goal of: 1) maximizing the wellbore loading rate so that multiple fractures are initiatied in the rock, yet 2) minimizing the peak pressures achieved in the wellbore so that the rock yield stress is not exceeded, and 3) maintaining high pressures and fluid availability in the wellbore to internally pressurize and extend initiated fractures.

An evaluation of three tailored-pulse loading parameters has been undertaken to access their importance in gas well stimulation technology. This numerical evaluation was performed using STEALTH finite-difference codes and was intended to provide a measure of the effects of various tailored-pulse load configurations on fracture development in Devonian gas shale. The three parameters considered in the sensitivity analysis were

- Loading Rate
- Decay Rate
- Sustained Peak Pressures

By varying these parameters in six computations and comparing the relative differences in fracture initiation and propagation the following conclusions were drawn:

- Fracture initiation is directly related to the loading rate applied to the wellbore wall. Loading rates of 10, 100 and 1000 GPa/sec were modeled.

- If yielding of the rock can be prevented or minimized, by maintaining low peak pressures in the wellbore, increasing the pulse loading rate, to say 10,000 GPa/sec or more, should initiate additional multiple fractures.

- Fracture initiation does not appear to be related to the tailored-pulse decay rate. Fracture extension may be influenced by the rate of decay. The slower the decay rate, the longer the crack extension.

- Fracture initiation does not appear to be improved by a high pressure plateau in a tailored-pulse. Fracture propagation may be enhanced if the maintained wellbore pressure plateau is of sufficient magnitude to extend the range of the tangential tensile stresses to greater radial distances.

PREFACE

The Eastern Gas Shales Project (EGSP) of the Department of Energy (DOE) has the goal of examining marginal gas resources and to determine what methods would be required to extract the vast amounts of natural gas trapped in eastern Devonian shales. As part of this project the Morgantown Energy Technology Center (METC) is conducting a research program to evaluate stimu- ation technologies in these relatively impermeable gas shales. One aspect of this program is concerned with numerical model development which would be used in assessing the suitability of various stimulation treatments. Part of this study is being conducted by Science Applications, Incorporated (SAI) under contract to METC. This report presents the results of a computational evaluation of the tailored-pulse-loading concept in stimulating Devonain gas shale. The analysis addresses loading and decay rates intermediate to those of explosive and hydraulic stimulation treatments.

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1. INTRODUCTION

Because of the inherent low permeability of Devonian gas shale, any stimulation technique applied to it must entail same in-formation fracturing. A principal objective of explosive stimulation techniques has been the formation of multiple fractures and/or extending natural fractures by loading the rack dynamically. Tailored-pulse-loading represents a stimulation technique which has developed to optimize fracture formation and growth. The desired result is to create cracks of adequate extent in the preferred direction to intersect as many gas bearing natural fractures as possible, without the wellbore damage typically associated with conventional explosive borehole shooting. A detailed knowledge of the relationships between the processes controlling rock fracture and the stress history of the dynamic loading is a necessary requirement in efforts to optimize the explosive stimulation pressure-time history. Much recent research has been directed towards this understanding of the stimulation phenomenon and several stimulation processes have been developed to quantify and demonstrate the pulse tailoring concept.

The optimized pulse would avoid limitations inherent in both hydraulic fracturing and conventional explosive fracturing. Hydraulic fractures, which are initiated and propagated at pressures that are slightly higher than the minimum in situ stress and for pumping times that are on the order of hundreds of seconds, typically produce only a single-pair of fractures where orientation is aligned with the in situ stresses. Conventional explosive detonations, which usually have peak pressures that are orders of magnitude above the in situ stresses and occur in microseconds, often cause considerable borehole crushing and leave a residual compressive stress zone around the wellbore. The wellbore damage and stress cage will often seal off any cracks that are formed further from the wellbore. A tailored pulse would incorporate the benefits of hydraulic and explosive fracturing by imparting a controlled pressure load such that: 1) the peak radial stress is below the rock flow stress, yet above the in situ stress level; 2) the peak circumferential stress is above the tensile strength of the rock; 3) the initial loading rate is large enough to initiate multiple fractures; and 4) the duration of the pulse and the permanent gases generated by the explosive detonation or propellant burning is sufficient to extend the multiple fractures relatively long distances.

Initial efforts on tailoring the borehole pressure pulse, to satisfy the above mentioned conditions, were carried out by Physics International and have resulted in the Dynafrac process (6). Subsequent efforts have been performed by Kinetech Corporation (Kinefrac, 4) and Sandia Laboratories (Gas-Frac, 8). The Dynafrac process uses a fast loading-rate explosive pulse to initiate multiple fractures with a superimposed slow burn-rate propellant pulse (as the explosive pulse decays) to extend the fractures. Kinefrac and Gas-Frac use deflagrating charges (propellants) with loading rates slower than explosives but large enough to initiate multiple fractures. Bath are high gas generators with low enough peak amplitudes to minimize bore-hole crushing and stress cage development. Abundant gas generation maintains the pulse long enough to permit the high pressure gases in the borehole to enter and extend the created multiple fractures. A buffering fluid (water) is employed in the Kinefrac and Dynafrac process to provide the desired loading rates while restricting peak pressures to below those which cause bore-hole damage by crushing and shear deformation of the rock.

Analytical, numerical, and laboratory and field experimental programs are currently being conducted to evaluate the potential for multiple fracture development and the influence of tailored-pulse-loading. As a part of this effort, Science Applications, Inc. (SAI) is conducting a research program to numerically evaluate a number of unconventional wellbore stimulation techniques. This report summarizes a parameter sensitivity analysis that was performed to determine the influence of several important aspects of the tailored-pulse-load on fracture initiation and propagation.

2. PARAMETER SENSITIVITY ANALYSIS OF TAILORED-PULSE LOADING

SAI's current effort in evaluating the concept of tailored-pulse-loading is concerned with the fracture development in Devonian gas shale as a result of six generic tailored-pulse loads. The initiation and propagation of multiple cracks generated at the wellbore wall is expected to be directly related to the rate at which a loading pulse rises and decays. By numerically modeling the effects of a tailored-pulse load we can begin to identify the combinations of loading rates and decay functions that are responsible for the generation of optimal fracture patterns.

The STEALTH* (5) time-explicit finite difference codes were used in this evaluation. Material descriptions, boundary conditions and model geometry were defined to model six tailored-pulse loads on a wellbore wall in Devonian gas shale. The models were designed to replicate typical in situ conditions. The calculations performed were one-dimensional and cylindrical, describing an infinitely long wellbore. Because these were primarily scoping calculations to assess general response and parameter sensitivity and were not concerned with wellbore end effects or time-lapse effects, one-dimensional computations were considered the most cost-effective method to describe the radial and circumferential response desired. Since the analysis was one-dimensional, pre-existing shale bedding planes (i.e., initial fractures) were not modeled. The shale model, therefore, represents a homogeneous, isotropic, and initially unfractured rock mass.

As input to the STEALTH/CAVS computation, the material behavior of the gas shale required appropriate constitutive equations describing the elastic response, yielding and the plastic response, compressibility/compactability and tensile fracture. Science Applications has recently completed a survey (3) of the Devonian gas shale static and dynamic mechanical properties. A summary of the material properties and initial conditions used in these calculations, taken from Reference 3 is presented in Table 1. Compressibility of the gas shale is modeled using the equation-of-state description shown in

*STEALTH (Solids and Thermal Hydraulic code for EPRI adapted from Lagrange TOODY and HEMP) developed under EPRI contract RP-307.

Figure 1. The yield envelope used in the isotropic plasticity model is shown in Figure 2, and was constructed from the results of a series of static triaxial tests on a brown gaseous Devonian gas loaded parallel to the bedding planes. The tensile failure of the shale is modeled using the CAVS (Cracking and Void Strain) fracture model. Its use in STEALTH and its theoretical basis is described in Reference 7. Example computation results for explosively loaded deep wellbore are presented in Reference 1. Details of the crack propping sub-models are described in Reference 2. Initial stress conditions have been defined to model in situ conditions at a depth of ≃ 325 meters. Assuming a 1 psi/foot of depth for the overburden stress and 0.7 psi/foot of depth for the horizontal stresses, the initial vertical stress is 7.35 MPa and the horizontal stresses are 5.15 MPa. The geometry and zoning of the one-dimensional, cylindrical model is shown in Figure 3.

The purpose of these calculations is to understand the influence of the shape of an applied wellbore pressure pulse on the fracture initiation and propagation in the shale. Computationally the pulses are applied with a defined pressure boundary history. The rate at which the pulse rises and the shape of its decay are parameters that could affect the number and extent of cracks developed. The pulse loading and decay rates for each of six cases are listed in Table 2. It should be noted that in each of the simulations pressurization of the cracks, possible through a submodel in CAVS, was not employed. This study directed its attention to stress wave fracture initiation and propagation only. Other reports have shown that the additional influence of internal crack pressurization will extend fractures to considerable radial distances, once they are initiated by the propagating stress wave. The models have been divided into three basic groups with either the loading rate or decay rate being held constant for each group and are discussed below.

2.1 Group 1 Calculation Description and Results

The primary interest in this first set of calculations was to evaluate the effect of the tailored-pulse loading rate on the induced fracture development around the wellbore. Slow, intermediate and fast rising pulses each with identical decay functions are shown in Figure 4. The three different pulses, TPL1, TPL2 and TPL3, were modeled as the applied wellbore pressure histories for Case 1, Case 2, and Case 3, respectively. Loading rates were chosen to bracket the range commonly addressed by existing slow and intermediate rate tailored-pulse stimulation treatments, particularly those using propellants. Preliminarily, it was expected that the slower loading rate would initiate fewer multiple cracks than the faster loading rate. A lower bound of a single pair of cracks would be expected for quasi-static loading.

Field observations of Sandia (8) from three experiments in ash-fall tuff have shown a dependence of the number of initiated radial fractures on the pulse loading rate. With a pulse loading rate of 0.6 GPa/sec a single pair of opposing fractures developed. Loading at a rate of 140 GPa/sec, 7 to 12 fractures were induced. At a rate of greater than 10,000 GPa/sec as many as 16 multiple fractures were initiated although their radial extend was minimal because of the yielding that occurred as a result of the high peak wellbore pressure.

To preclude yielding of the near-wellbore rock, which will cause stress wave modifications which may prohibit hoop tensile failure, each of the three calculations of this group were performed with a defined pulse which has the same low peak pressure (50 MPa). This maximum pressure does not cause yielding of the rock, and the sensitivity analysis was thus a comparison of the loading rate only. The loading rates of the calculations in this group were 10, 100, and 1000 GPa/sec.

Results of the Case 1, Case 2 and Case 3 calculations are shown in Figures 5 through 9, Figures 10 through 14 and Figures 15 through 19, respectively. Figures 5, 10 and 15 show the radial and tangential stress histories at the borehole wall for each of the three cases. Figures 6, 11 and 16 show similar histories at 0.5 meter radial distance from the wellbore center. The lack of near-wellbore yielding in each case is illustrated by the elastic rebound of the wellbore wall. Figures 7, 12 and 17 are time histories of the radial position of the wellbore wall for Cases 1, 2 and 3, respectively.

Figures 8, 13, and 18 are the CAVS calculated fracture patterns for the three cases. The slow loading rate (10 GPa/sec) simulation (Case 1) induces a single crack as shown in Figure 8. A pair of cracks, as mentioned above, would be expected to duplicate the field observations. The difference is largely attributed to the present CAVS crack odometer description (2) which uses a sequential description for crack growth rather than a consecutive crack growth description. The sequential odometer first allows a single crack to grow across a computational zone, then a second crack to grow in the opposite radial direction. After a pair of zone through-cracks develop, additional cracks (defined by the odometer) successively subdivide the inter-crack spacing; creating 4, 8, 16, ... cracks. This calculation illustrates a deficiency with the present odometer definition, which has been recognized by SAI for some time. Current efforts are being directed towards the definition of an odometer which provides for consecutive cracking, whereby cracks are described using a 2, 4, 8, 16,.... crack development scheme but where cracks need not be zone through-cracks before new partial cracks are initiated. The new approach will allow for the possibility of any number of partial cracks, growing consecutively, and will be strain rate dependent.

Figures 13 and 18 provide a comparison of the effects of two different wellbore pressure loading rates. The calculation with a loading rate of 100 GPa/sec (Case 2) shows the development of four radial cracks. Case 3 (1000 GPa/sec loading rate) results show the development of eight cracks. The significance of these crack patterns is that if yielding is prohibited or minimized, an increased loading rate will induce a greater number of multiple fractures. A still higher loading rate, for example 10,000 GPa/sec, would be expected to produce 16 (or mare) radial cracks (as suggested by Sandia's field observations described above) initiating at the wellbore wall.

Figures 9, 14 and 19 are void strain plots as a function of radial distance in the rock. The void strain (a measure of the crack width) is comparable in each of the three cases. Note from the figures that as the applied wellbore pressure pulse decreases and the tangential stresses relax, the cracks close in response to the increased compressive stresses. The residual, but small, void strain distribution in each case is a reflection of the crack jumbling sub-model that is included in the CAVS fracture model.

2.2 Group 2 Calculation Description and Results

In the second set of calculations pressure-time histories applied to the wellbore wall had identical loading rates (100 GPa/sec of Case 2) but substantially different pulse decay rates. Figure 20 shows the three tailored-pulse loads applied in this group of calculations. Comparison is made between Case 2 of the first group of calculations described in Section 2.1 and the two additional calculations of this group (i.e., Case 4 and Case 5).

A comparison of the CAVS fracture plots for Cases 4 and 5, shown in Figures 21 and 22, and that of Case 2 shown in Figure 13, indicate little apparent difference in the induced crack pattern. Slight improvement can be detected for the slower decay rates which is attributed to the longer duration of the induced tangential tensile stress which occurs in the slower decaying pulses.

2.3 Group 3 Calculation Description and Results

The purpose of this group of calculations is to evaluate the effect on the crack development of a maintained pressure plateau at the maximum pulse pressure. Figure 23 illustrates the applied tailored-pulse of Case 6 (TPL6). The pulse described for Case 6 is similar to Case 2, but a sustained pressure level is maintained for 2.5 milliseconds after the peak pressure is reached and before pressure decay begins. Figure 23 also shows the Case 2 (TPL2) and Case 4 (TPL4) pulses for comparison. Maintaining the high wellbore pressure for an additional period of time would, as initially speculated, provide the maintained tangential tensile stress required for additional crack propagation of the already initiated cracks. No new crack initiation was suspected.

Calculation results of the Case 6 (TPL 6) simulation are shown in Figures 24 through 26. Figures 24 and 25 are stress histories in the shale at the wellbore wall and at a radial distance of 0.5 meters. Note the maintained high radial stresses in these two figures, reflecting the applied wellbore wall pressure history. The tangential stress shown in Figure 24, for the computational zone near the wellbore wall, exceeds the material tensile strength

(5 MPa) momentarily and quickly relaxes to zero in response to the stress relaxation associated with the crack free face development in that zone. The induced tangential stress, in this first shale zone, during the period of the high pressure plateau of the applied pulse is not tensile enough to initiate new cracks and thus during this period the stresses are relaxed to zero. Figure 25 shows the stress history in a zone at a greater radial distance than the longest induced crack (see Figure 26). Note here that the tangential and radial stress histories describe the applied pulse shape. No cracks have formed at this distance (the maximum hoop tensile stress does not exceed the material tensile strength) and no hoop stress relaxation occurs.

3. SUMMARY AND CONCLUSIONS

In support of the continued evaluation of the tailored-pulse-loading concept the analysis of three tailored-pulse loading parameters has been undertaken to access their importance in gas-well stimulation. This numerical evaluation was performed using STEALTH finite-difference codes and was intended to provide a measure of the effects of various tailored-pulse load configurations on fracture development in Devonian gas shale. The three parameters considered in the sensitivity analysis were

- Loading Rate,
- Decay Rate, and
- Sustained Peak Pressures.

By varying these parameters in six computations and comparing the relative differences in fracture initiation and propagation, the importance of each can be determined. Results far these analyses suggest the following:

- Fracture initiation is directly related to the loading rate applied to the wellbore wall. Far a pulse loading rate of 10 GPa/sec a single crack initiated and propagated to approximately 0.3 meter. For a pulse loading rate of 100 GPa/sec four equal length cracks developed to approximately 0.3 meter. For a pulse loading rate of 1000 GPa/sec eight cracks developed; four to a distance of approximately 0.3 meter and four to a distance of approximately 0.03 meter.

- If yielding of the rock can be prevented or minimized, by maintaining low peak pressures in the wellbore, increasing the pulse loading rate, to say 10,000 GPa/sec or more, should initiate additional multiple fractures.

- Fracture initiation does not appear to be related to the tailored-pulse decay rate. Fracture extension may be influenced by the rate of decay. The slower the decay rate, the longer the crack extension.

- Fracture initiation does not appear to be improved by high pressure plateau in a tailored-pulse. Fracture propagation may be enhanced if the maintained wellbore pressure plateau is high enough to extend the range of the tangential tensile stresses to greater radial distances.

In light of these conclusions, optimization of a wellbore tailored-pulse load should give consideration to maximizing the loading rate of the applied pulse in order to maximize multiple crack initiation. Faster loading rates generally are associated with larger peak borehole pressures because of the nature of explosive/propellant energy release. To achieve the desired multiple crack initiation without the detrimental effect of rock yielding, the pulse should have a fast rate of loading but with low peak amplitude. Incrementally increasing the loading rate and the peak pressure to determine the crossover point between maximum fracture initiation and detrimental wellbore yielding would be an area for further parameter sensitivity evaluation.

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TABLE 1. DEVONIAN GAS SHALE MECHANICAL PROPERTIES*

DENSITY		ρ	=	ρ_o/V, kg/m^3
		V	=	relative volume
		ρ_o	=	initial density, 2512 kg/m^3
ELASTICITY (isotropic)				
Compressibility (equation-of-state)	$\mu \geq 0$	P	=	$A + B\mu + C\mu^2$, Pa
- see Figure 1	$\mu < 0$	P	=	$A + B\mu$, Pa
		P	=	pressure
		μ	=	$(1-V)/V$
		V	=	relative volume
		A	=	-1.934×10^7 Pa
		B	=	6.741×10^9 Pa
		C	=	1.710×10^{11} Pa
Distortion (constant shear modulus)		G	=	1.444×10^{10} Pa
PLASTICITY (isotropic)				
Yield Stress -See Figure 2		Y	=	$A + \frac{1}{2}(B + C\sigma_m)^{\frac{1}{2}}$, Pa
		Y	=	stress difference
		σ_m	=	mean stress, Pa
		A	=	-1.001×10^8 Pa
		B	=	6.061×10^{16} Pa^2
		C	=	2.323×10^9 Pa
Yield Criterion				von Mises as defined in STEALTH
Flow Rule				non-associative Prandtl-Reuss as defined in STEALTH

TABLE 1. DEVONIAN GAS SHALE MECHANICAL PROPERTIES* (continued)

TENSILE FAILURE (isotropic)			
Virgin tensile strength	σ^{to}_{k}	=	5.03×10^6 Pa
CAVS ratio of crack initiation - to - crack propagation strength (constant)	R	=	2.0
CAVS crack initiation and propagation strengths adjusted according to the degree of nearby cracking	σ^{tc}_{k}	=	$\sigma^{to}_{k}(S^{N_k})$
	σ^{tc}_{k}	=	current crack initiation strength of three orthogonal cracks (k = 1,2,3), Pa
	S	=	1.05 (constant)
	N_k	=	number of zone through cracks
Tensile Bulk Modulus (constant)	TK	=	6.741×10^9 Pa
CAVS Crack Propping and Internal Pressurization			NO
IN SITU STRESSES (initial, anisotropic)			
Vertical (1067' at 1 psi per foot)	σ_z	=	7.35×10^6 Pa
Horizontal (1067' at 0.7 psi per foot)	$\sigma_x = \sigma_Y$	=	5.15×10^6 Pa
INITIAL JOINTS (simulating bedding planes)			No

*Compiled from Reference (3)

TABLE 2. SUMMARY OF TAILORED-PULSE-LOAD DESCRIPTIONS

	GROUP 1		
	TPL1	TPL2	TPL3
Loading Rate (GPa/Sec)	10	100	1000
Decay Constant D*	-500	-500	-500
Plateau Length (milliseconds)	0	0	0

	GROUP 2		
	TPL4	TPL2	TPL5
Loading Rate (GPa/Sec)	100	100	100
Decay Constant D*	-100	-500	-1000
Plateau Length (milliseconds)	0	0	0

	GROUP 2		
	TPL2	TPL4	TPL6
Loading Rate (GPa/Sec)	100	100	100
Decay Constant D*	-500	-100	-500
Plateau Length (milliseconds)	0	0	2.5

*The decay is an exponential function of time and the decay constant D where

$$P = 5 \times 10^{11} * e^{\Delta t * D}$$

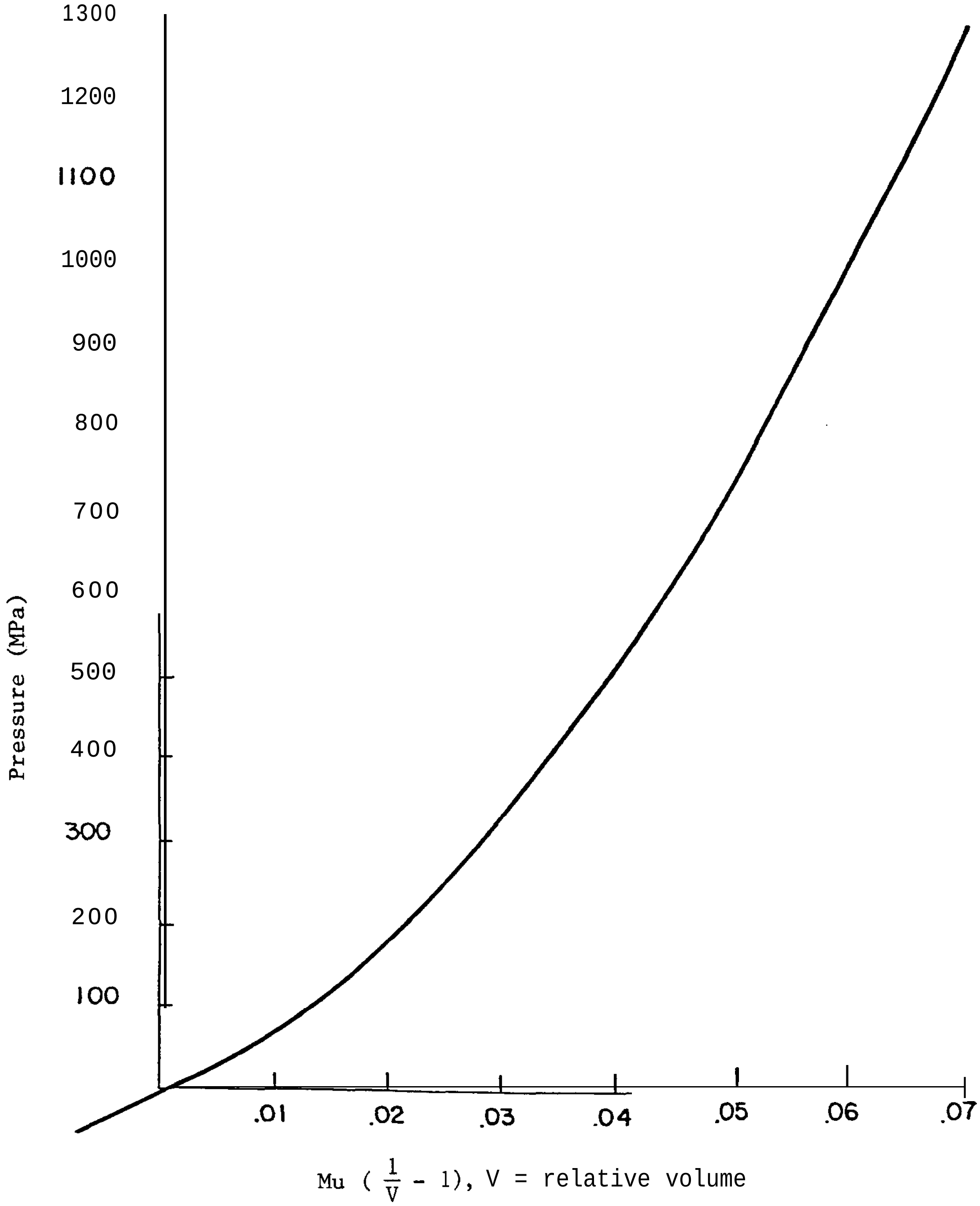


Figure 1. Equation-of-state for Devonian Gas Shale

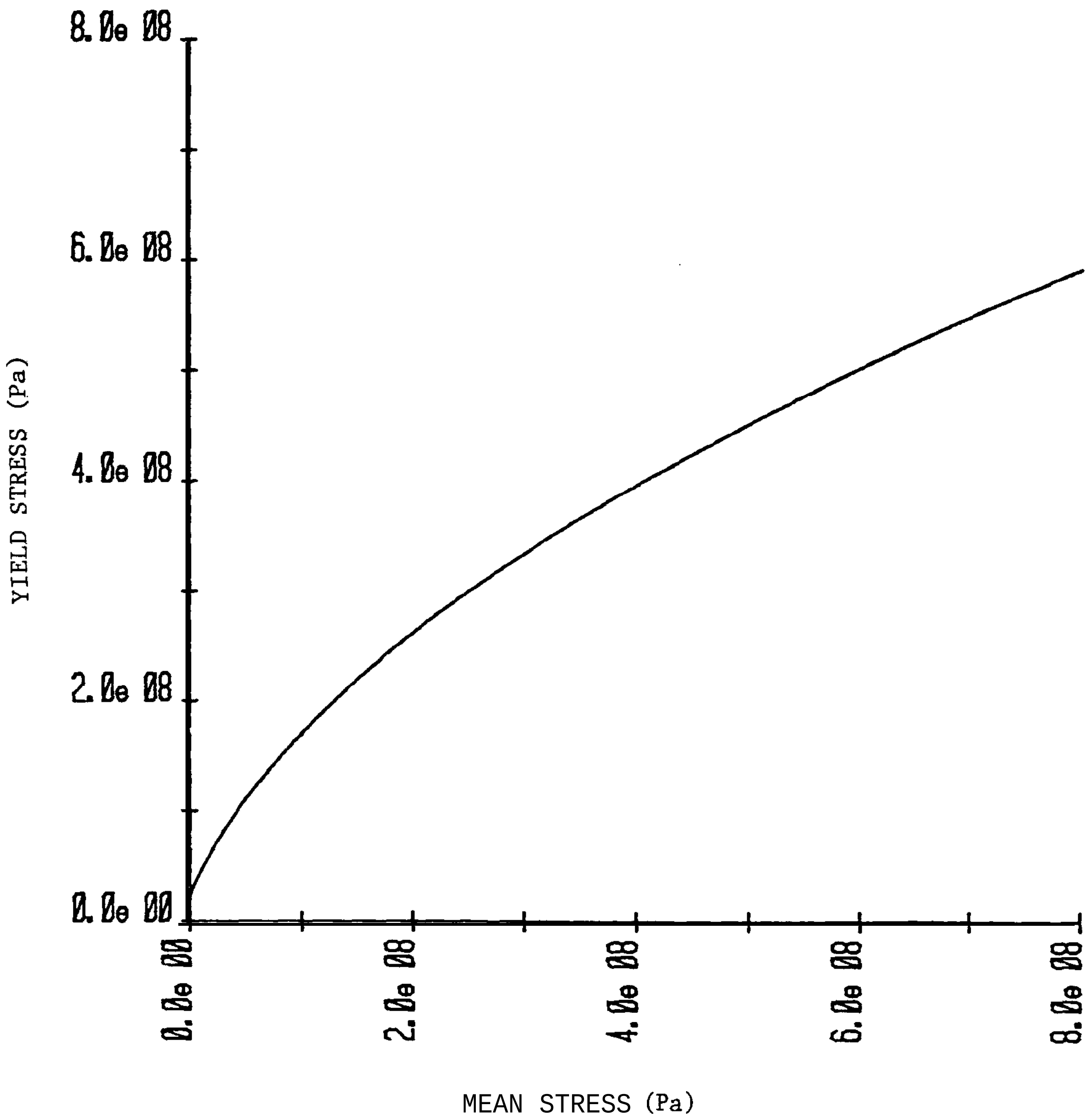
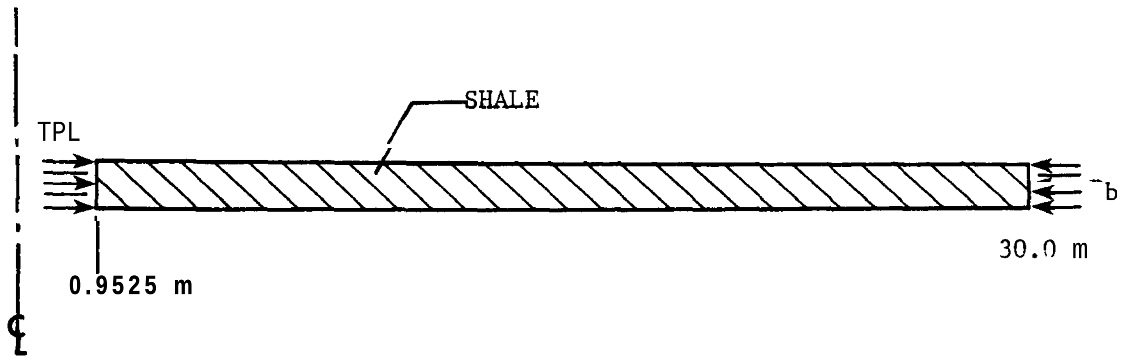


Figure 2. Yield Envelope for Devonian Gas Shale (Typical)



ZONING		INITIAL CONDITIONS	
Shale	76 Zones (geometric ratio = 1.075)	σ_v (shale)	-7.35×10^6 Pa
		σ_h (shale)	-5.16×10^6 Pa
		P_b (constant)	5.16×10^6 Pa
		TPL (variable depending on case)	

Figure 3. One-dimensional Cylindrical Geometry Calculational Model For Tailored-Pulse-Loading Simulations

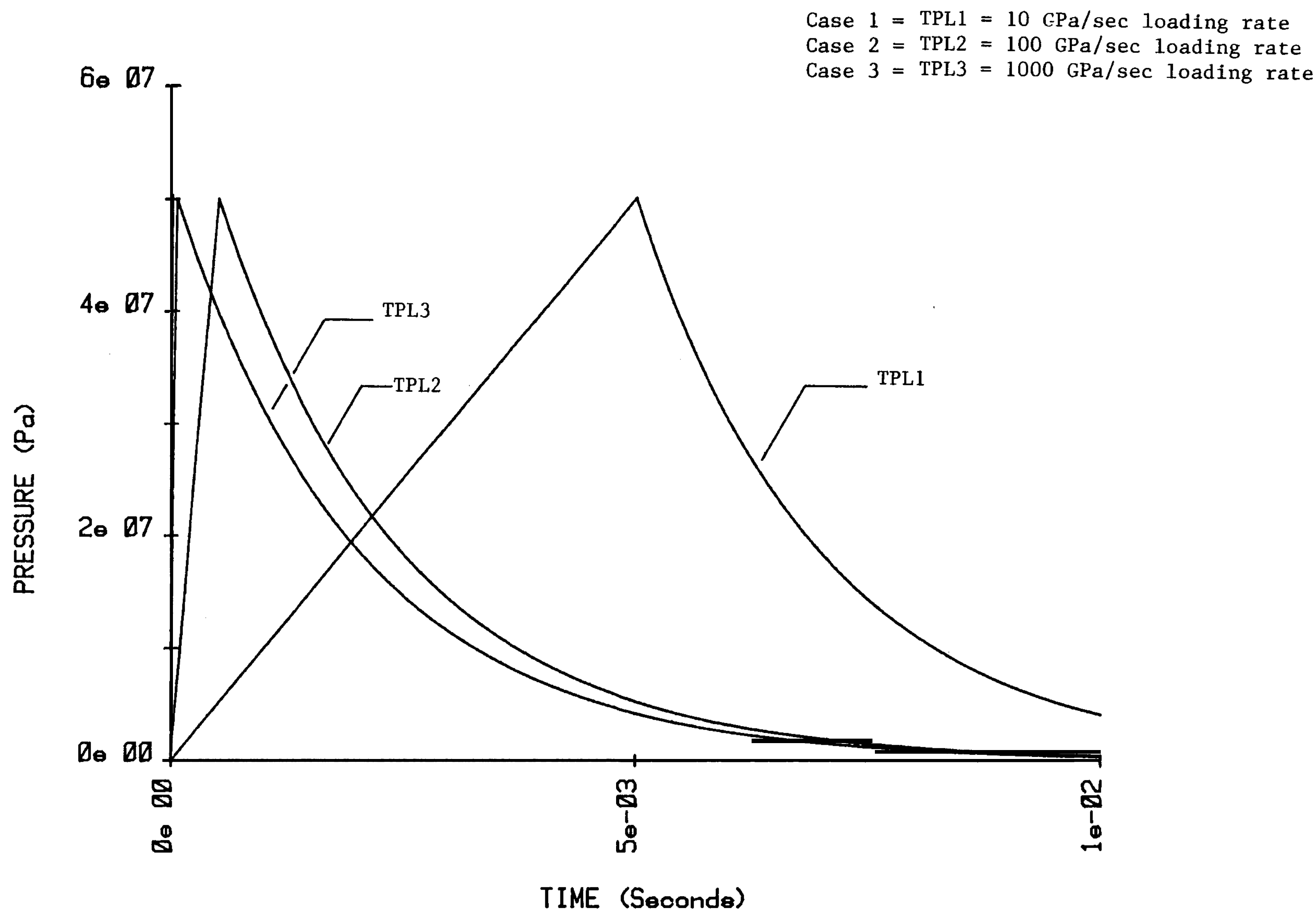
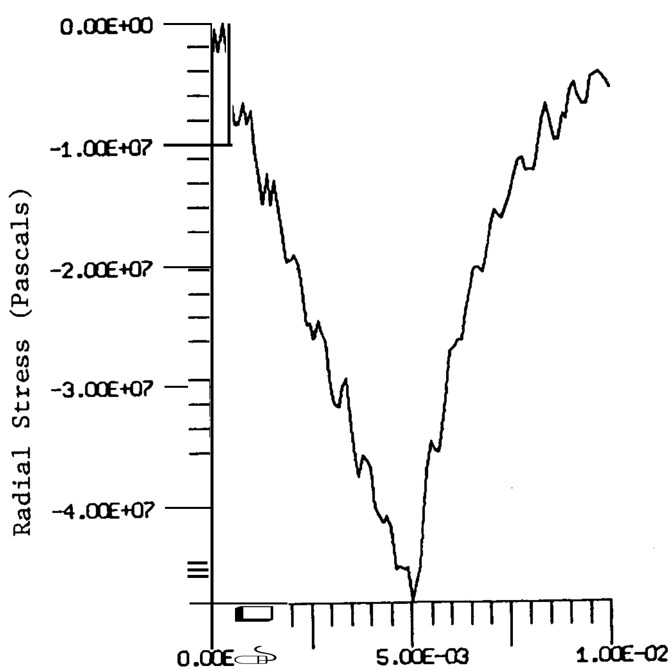
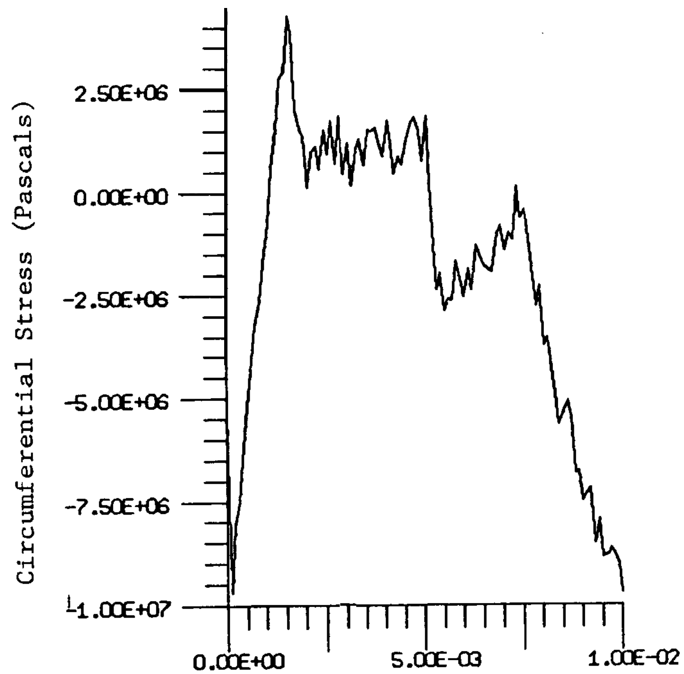


Figure 4. Group One Pressure-Time Histories Applied at Wellbore Wall

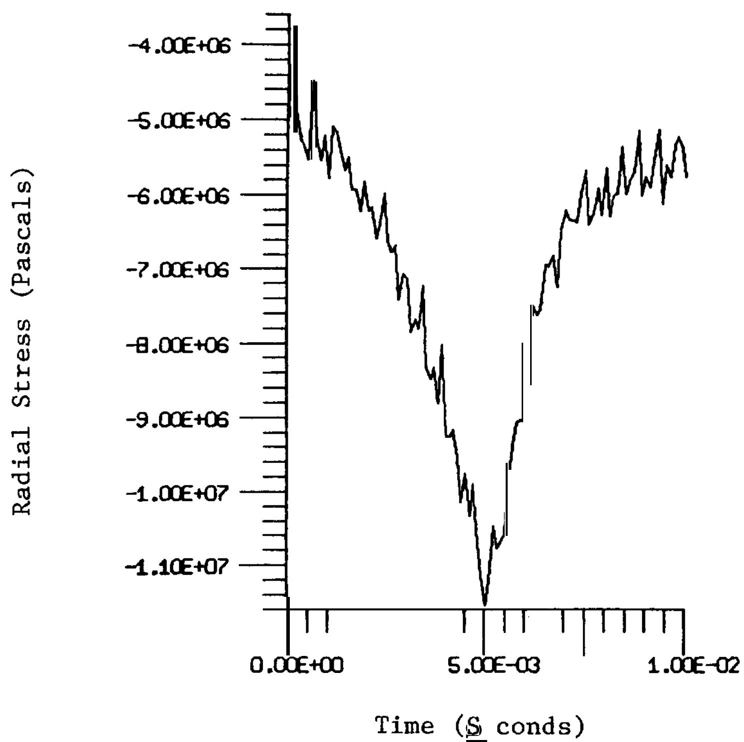


(a) Radial Stress

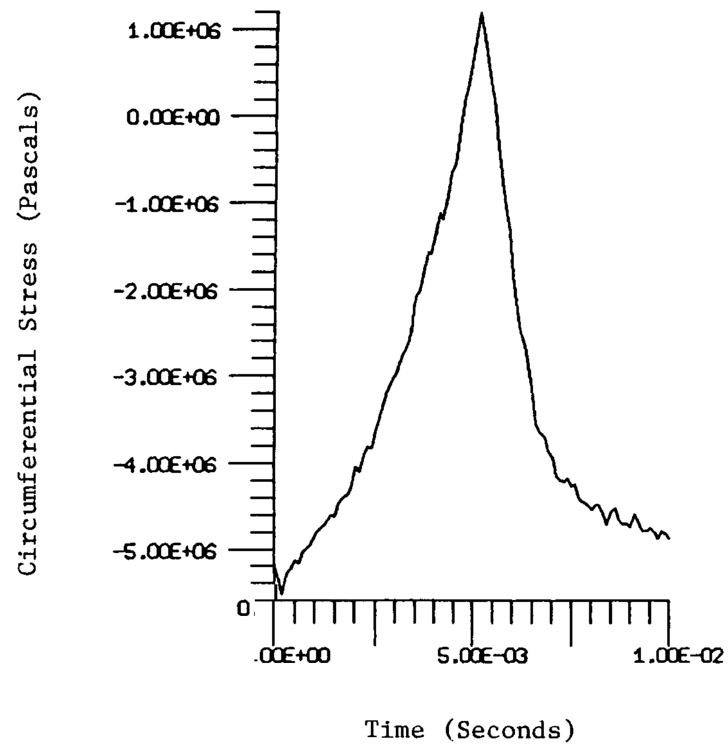


(b) Circumferential Stress

Figure 5. Case 1 - Stress History in Shale Adjacent to Wellbore Wall



(a) Radial Stress



(b) Circumferential Stress

Figure 6. Case 1 - Stress History in Shale Approximately 0.5 Meters from Wellbore Center

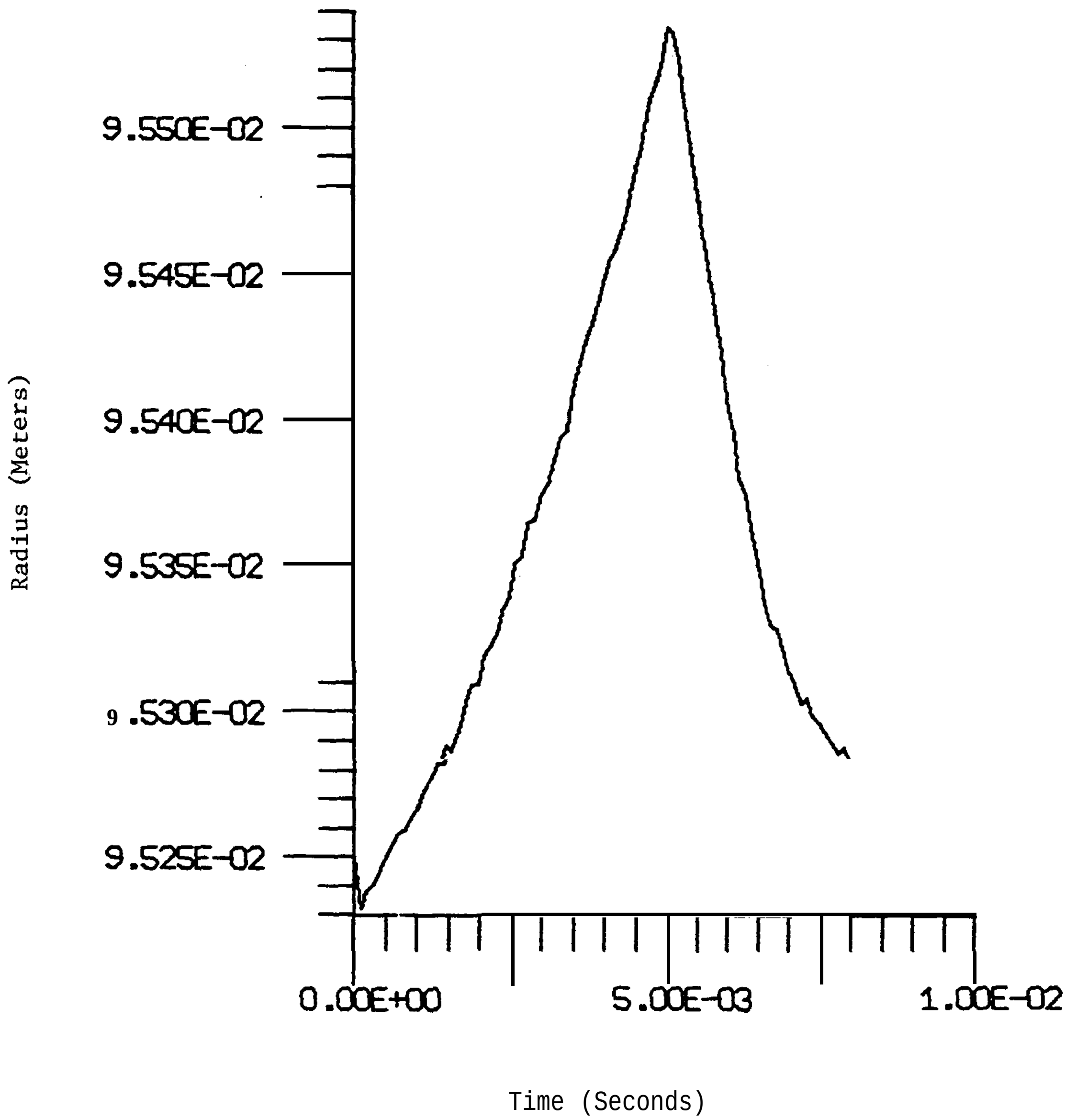


Figure 7. Case 1 - Wellbore Wall Radius-Time History

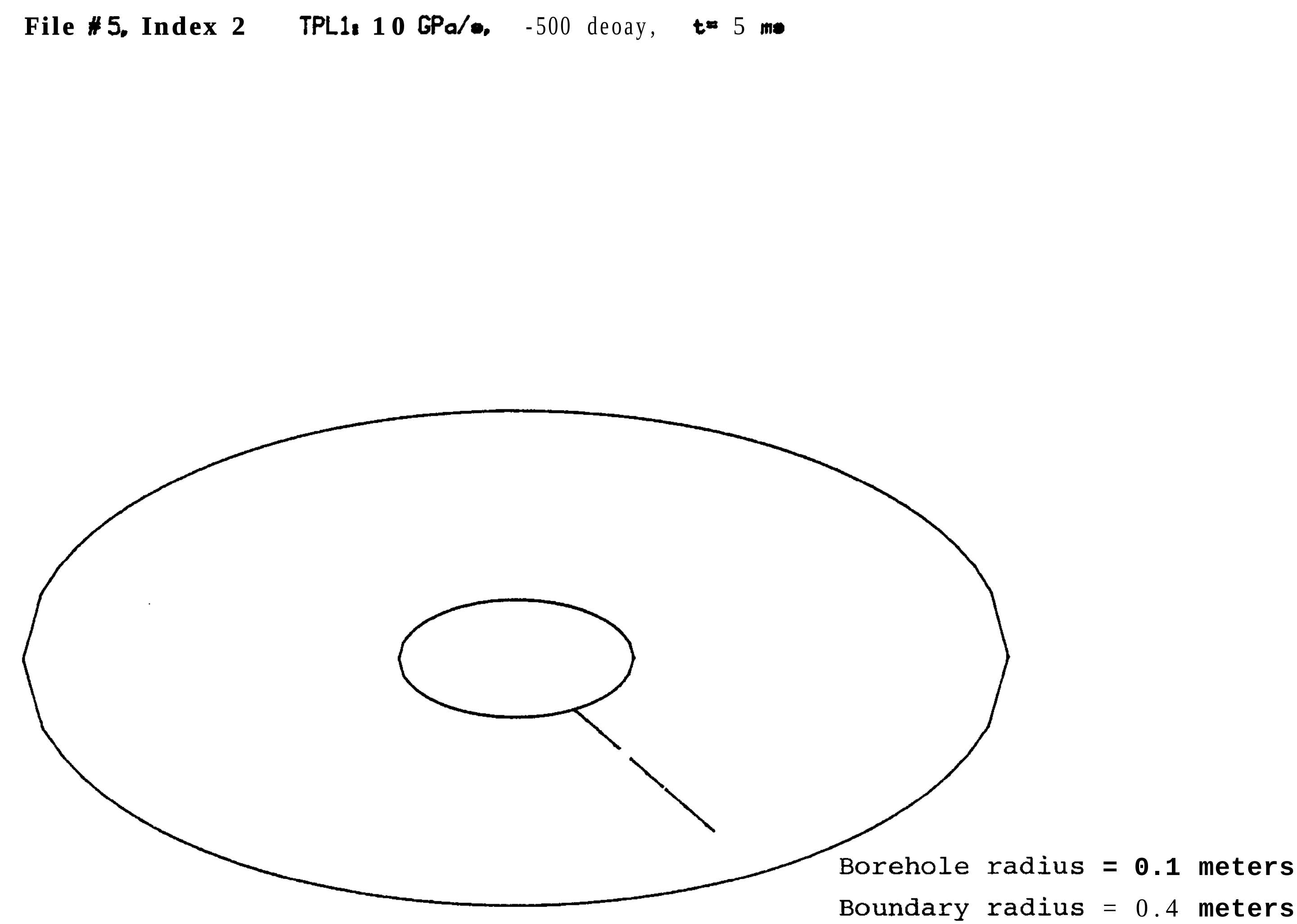


Figure 8. Case 1 - CAVS Fracture Plot at 10 Milliseconds
(No change after 5 Milliseconds)

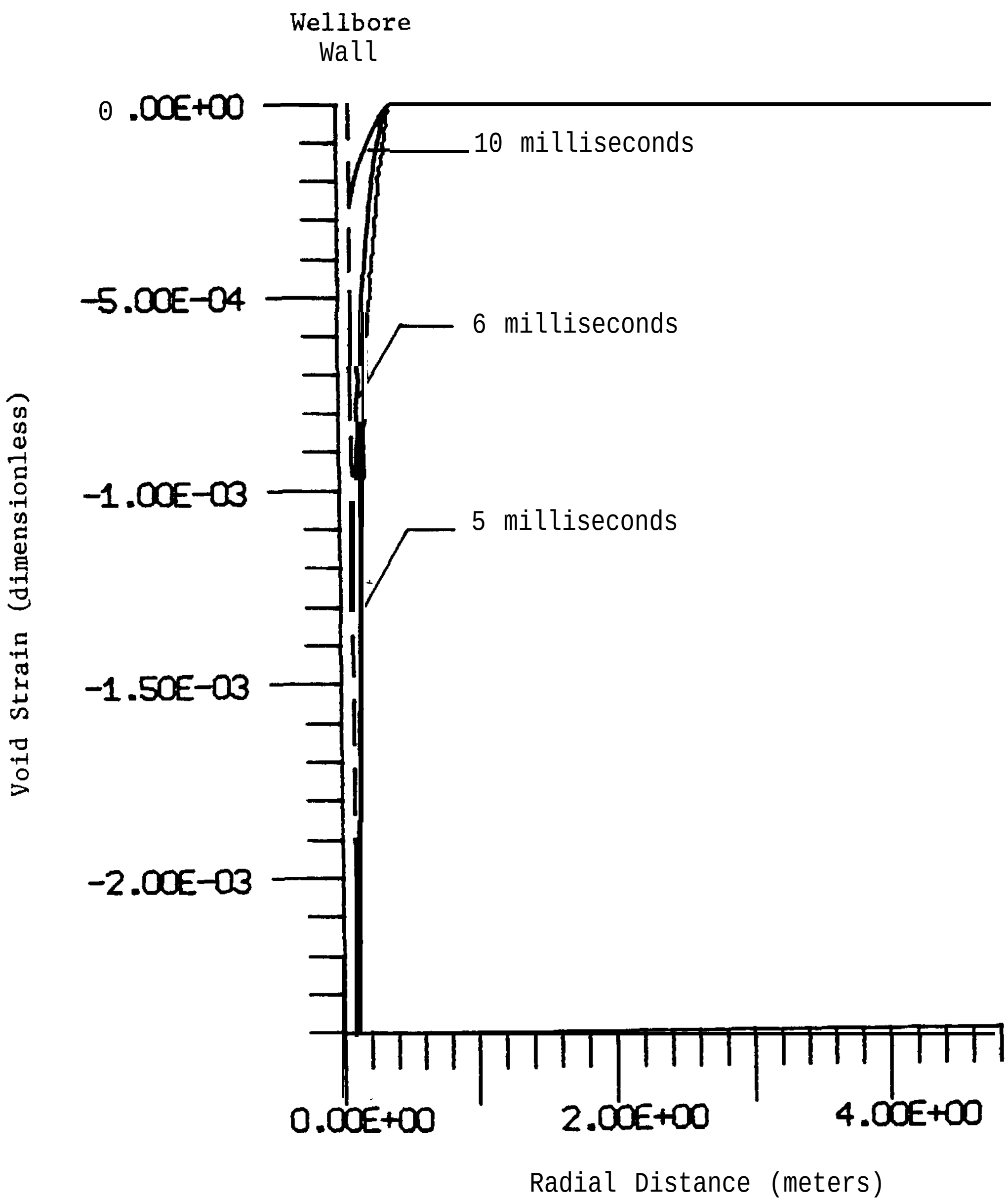
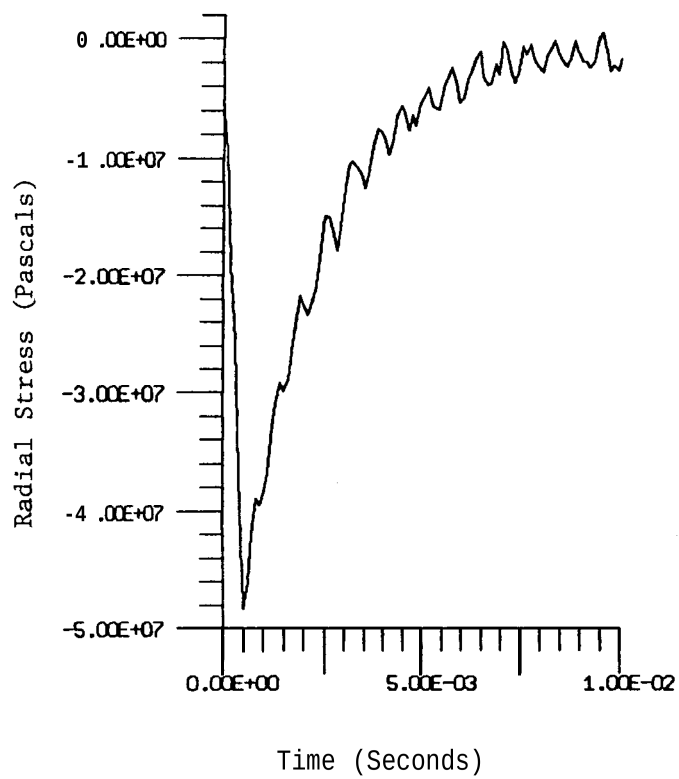
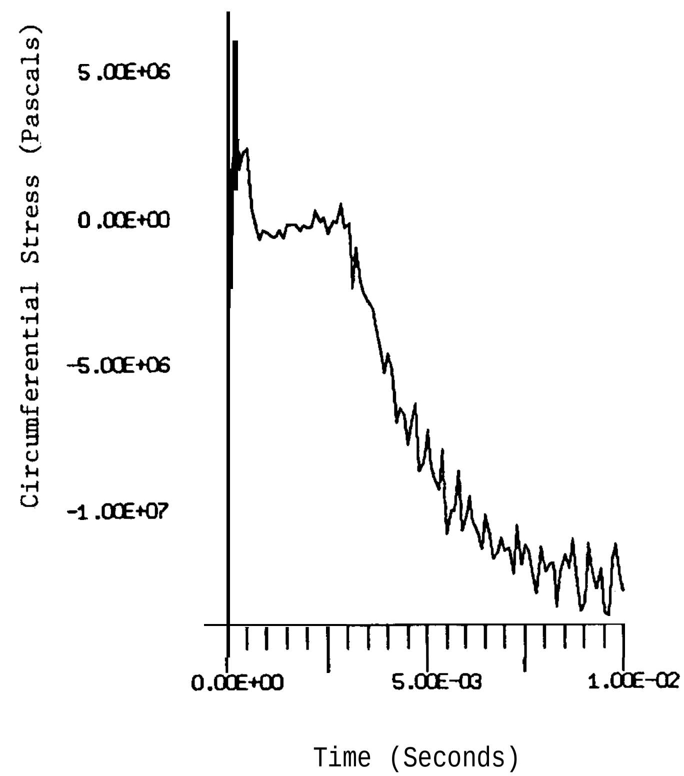


Figure 9. Case 1 - Crack Void Strain versus Radial Distance

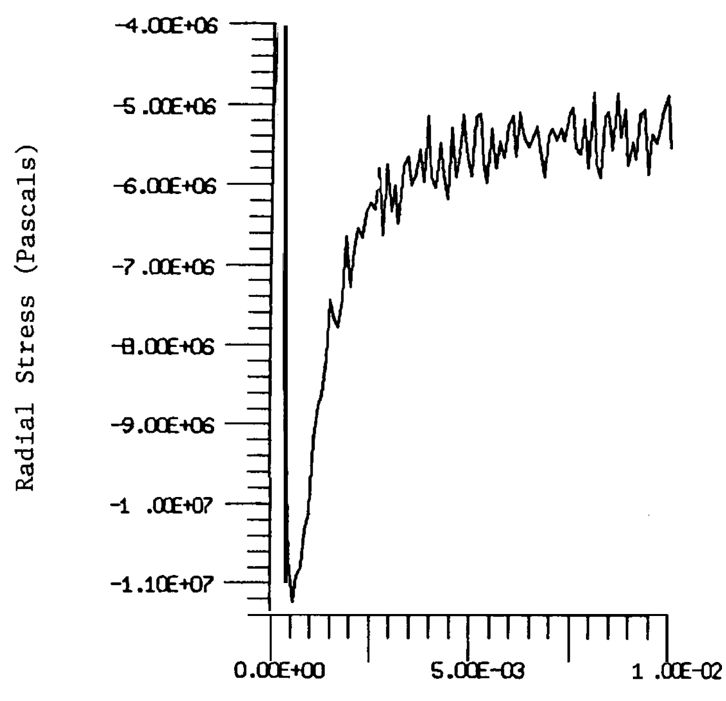


(a) Radial Stress

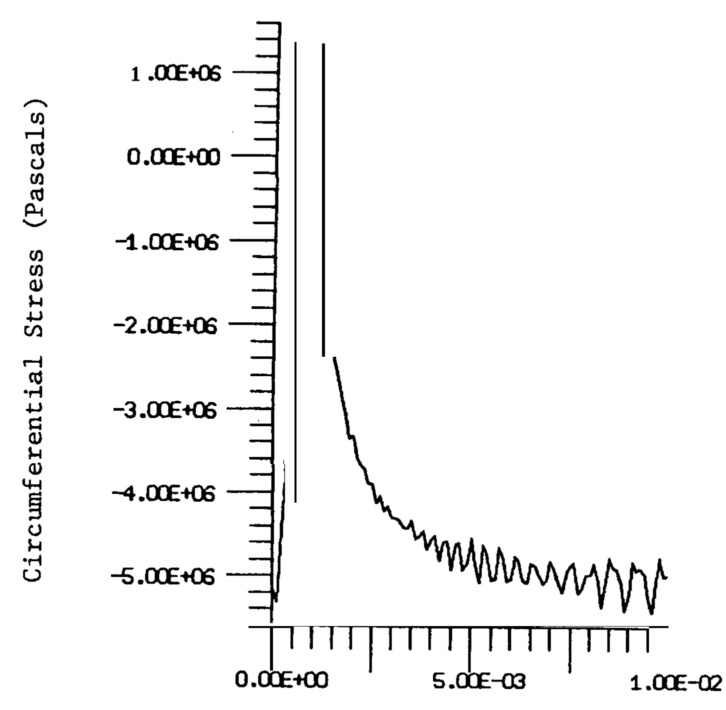


(b) Circumferential Stress

Figure 10. Case 2 - Stress History in Shale Adjacent to Wellbore Wall



(a) Radial Stress



(b) Circumferential Stress

Figure 11. Case 2 - Stress History in Shale Approximately 0.5 Meters from Wellbore Center

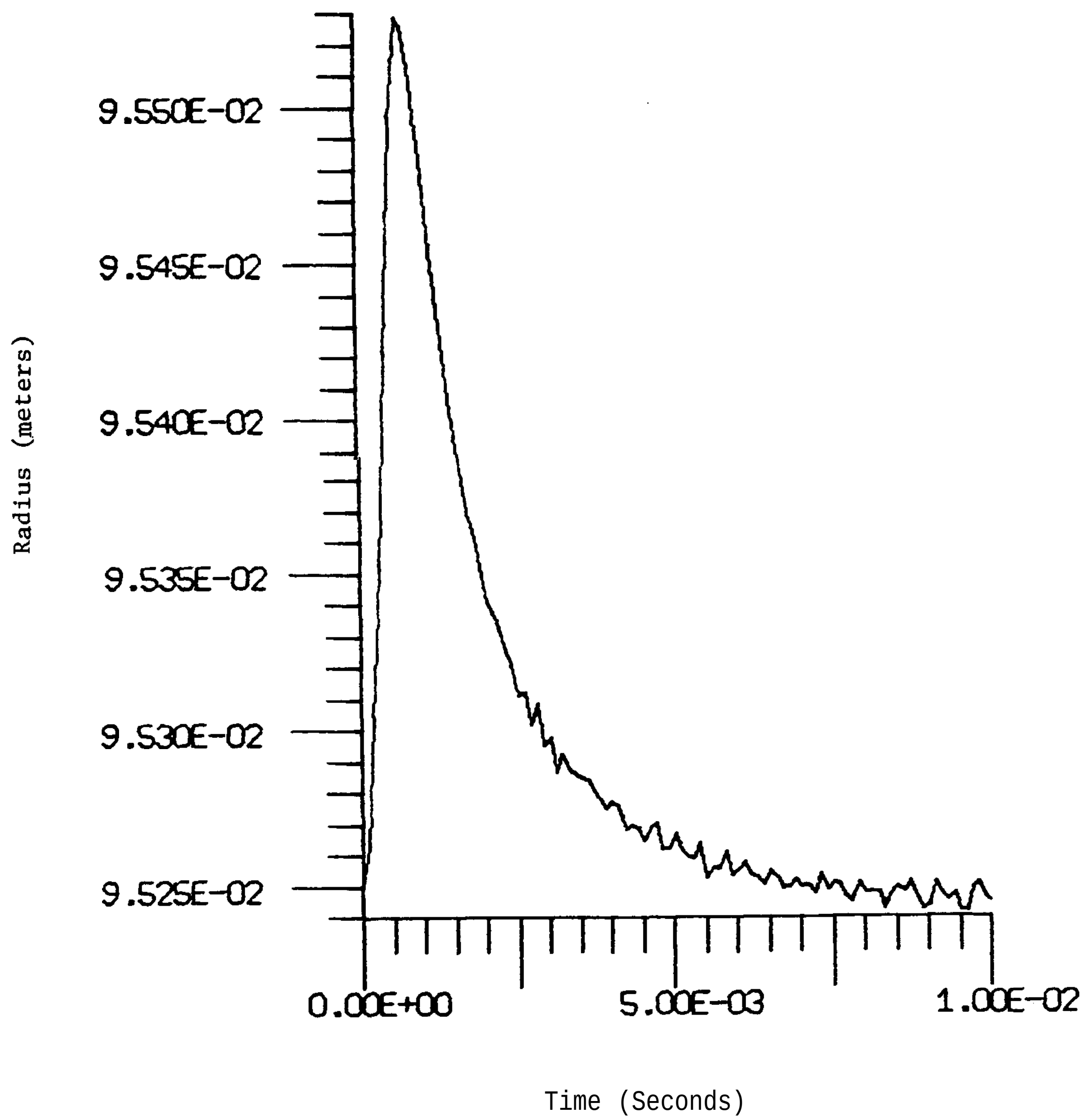


Figure 12. Case 2 - Wellbore Wall Radius-Time History

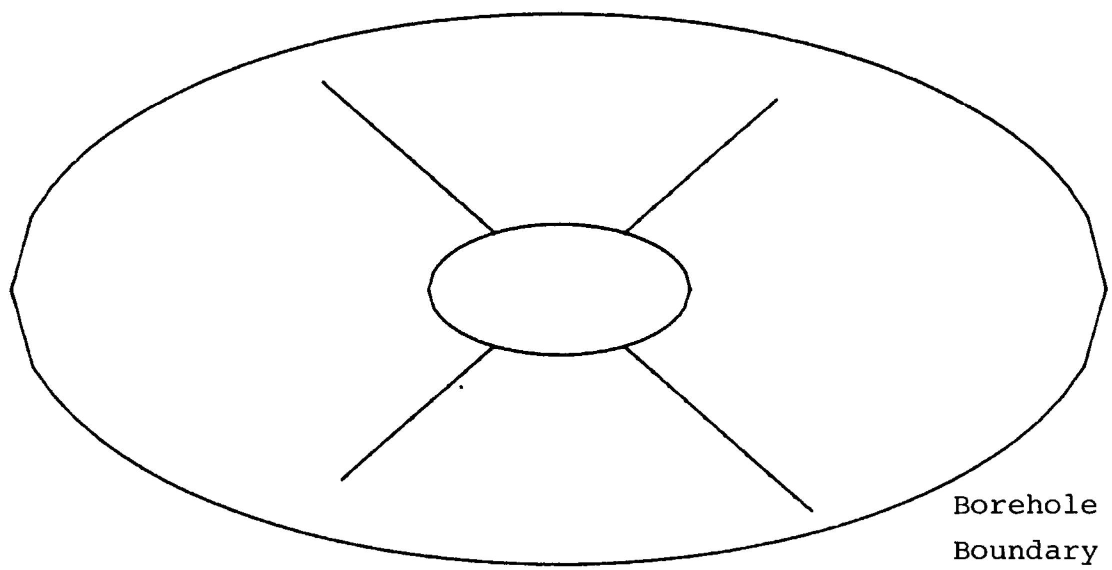


Figure 13. Case 2 – CAVS Fracture Plot at 10 Milliseconds
(No change after 1 Millisecond)

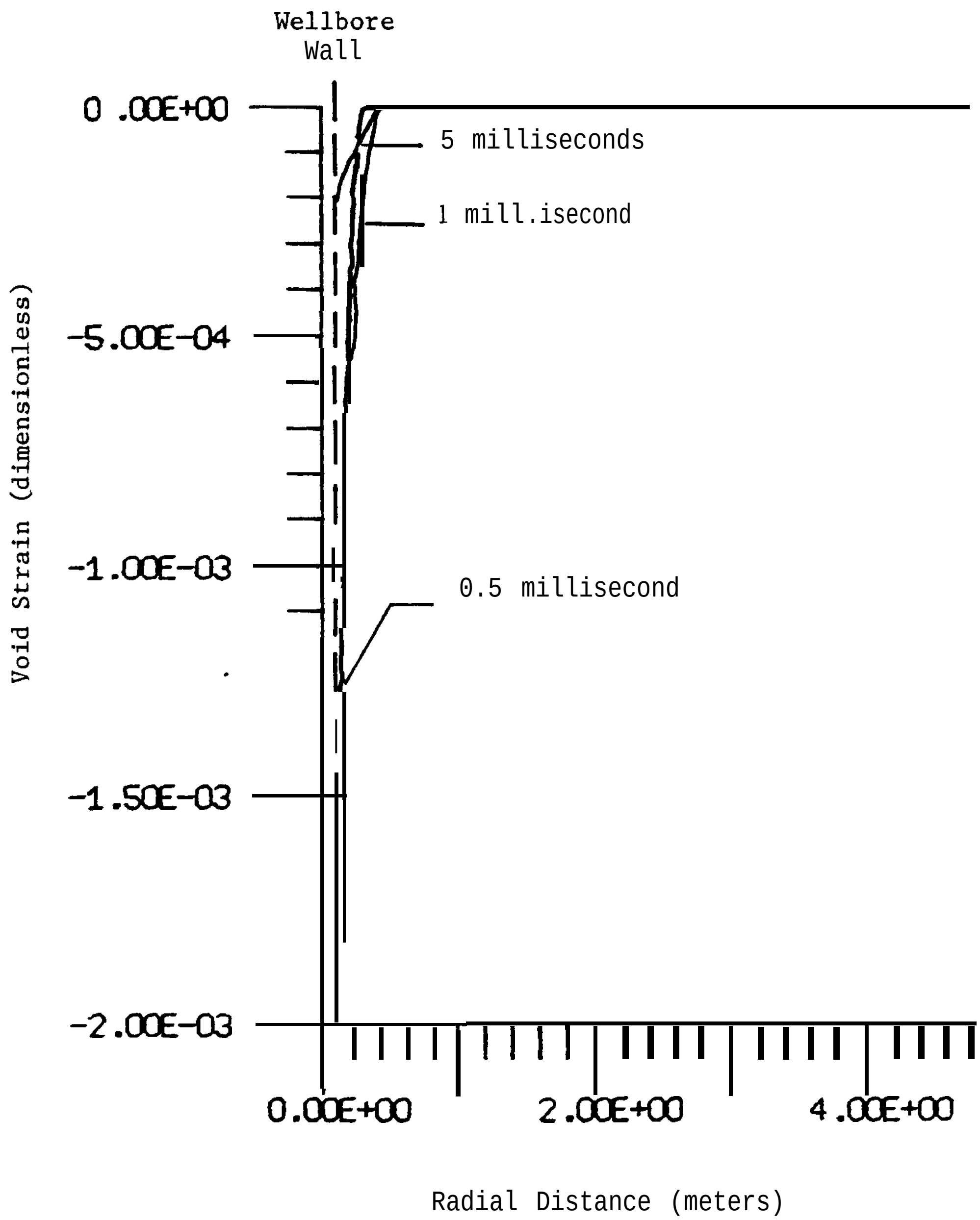
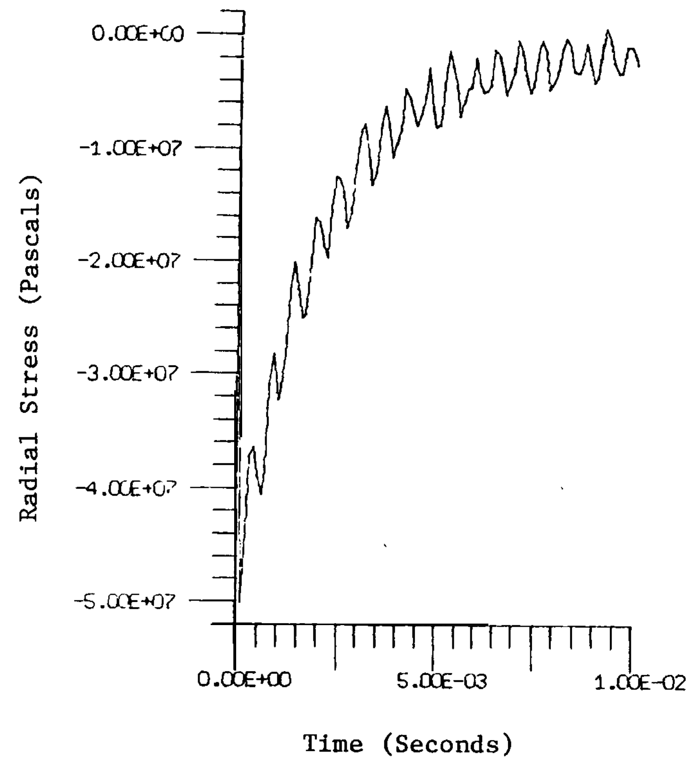
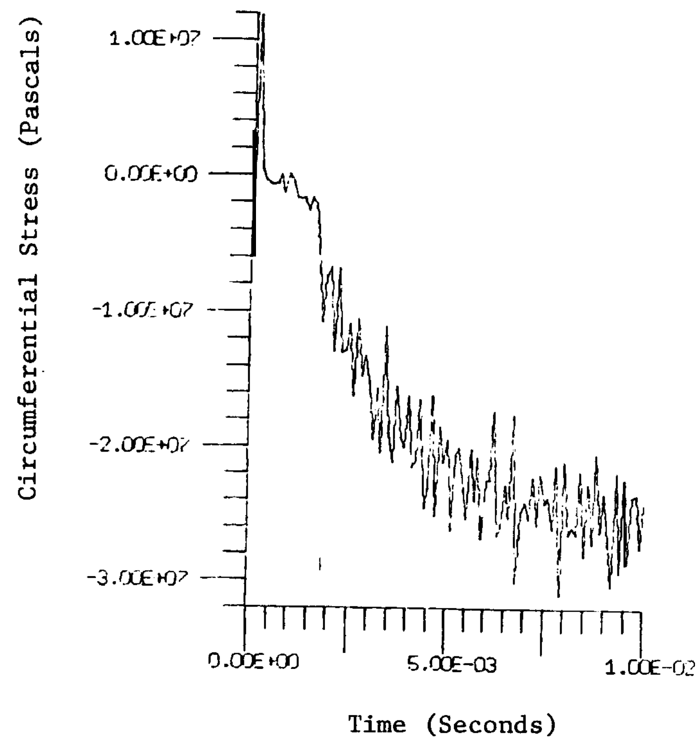


Figure 14. Case 2 - Crack Void Strain versus Radial Distance

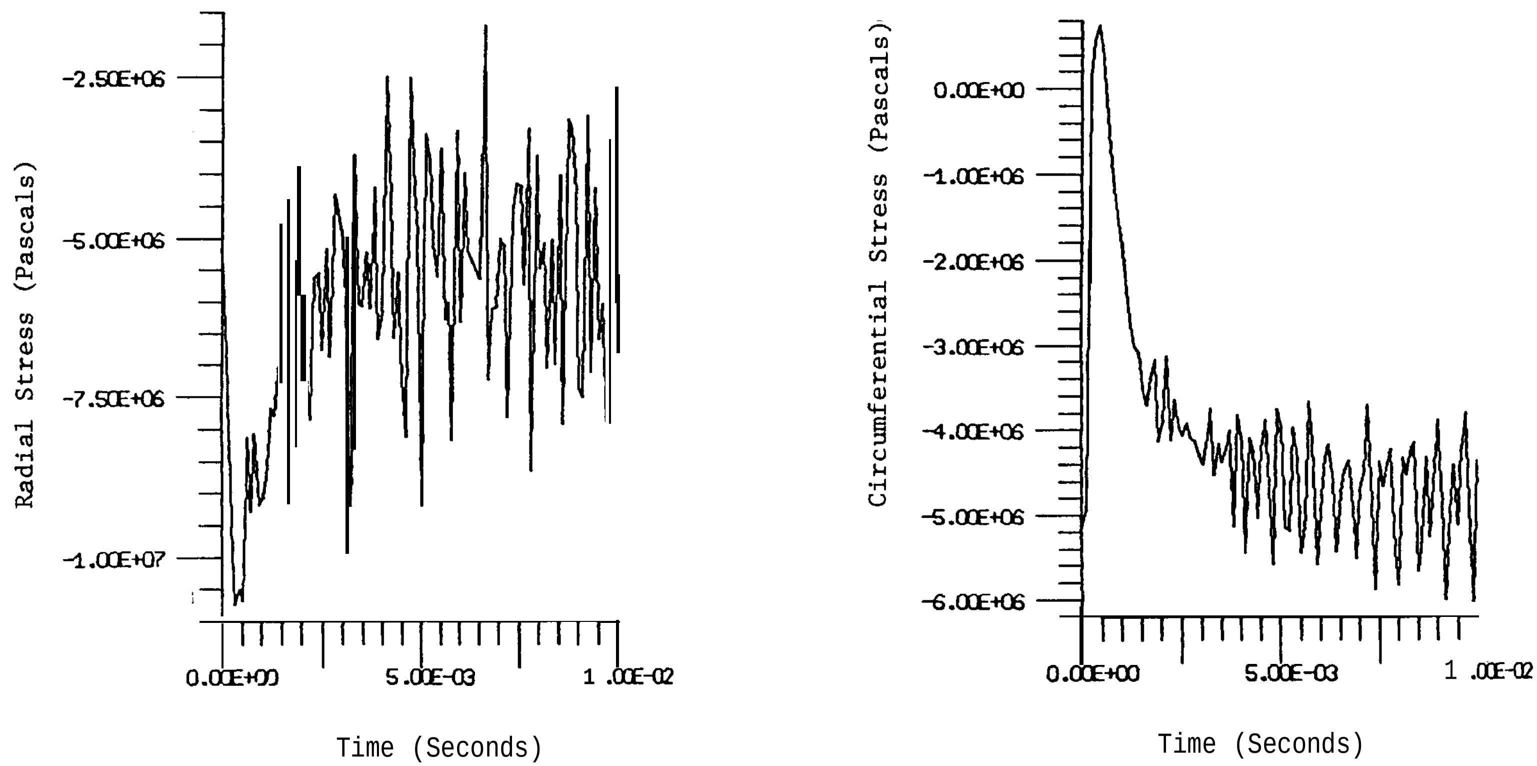


(a) Radial Stress



(b) Circumferential Stress

Figure 15. Case 3 - Stress History in Shale Adjacent to Wellbore Wal



(a) Radial Stress

(b) Circumferential Stress

Figure 16. Case 3 - Stress History in Shale Approximately 0.5 Meters from Wellbore Center

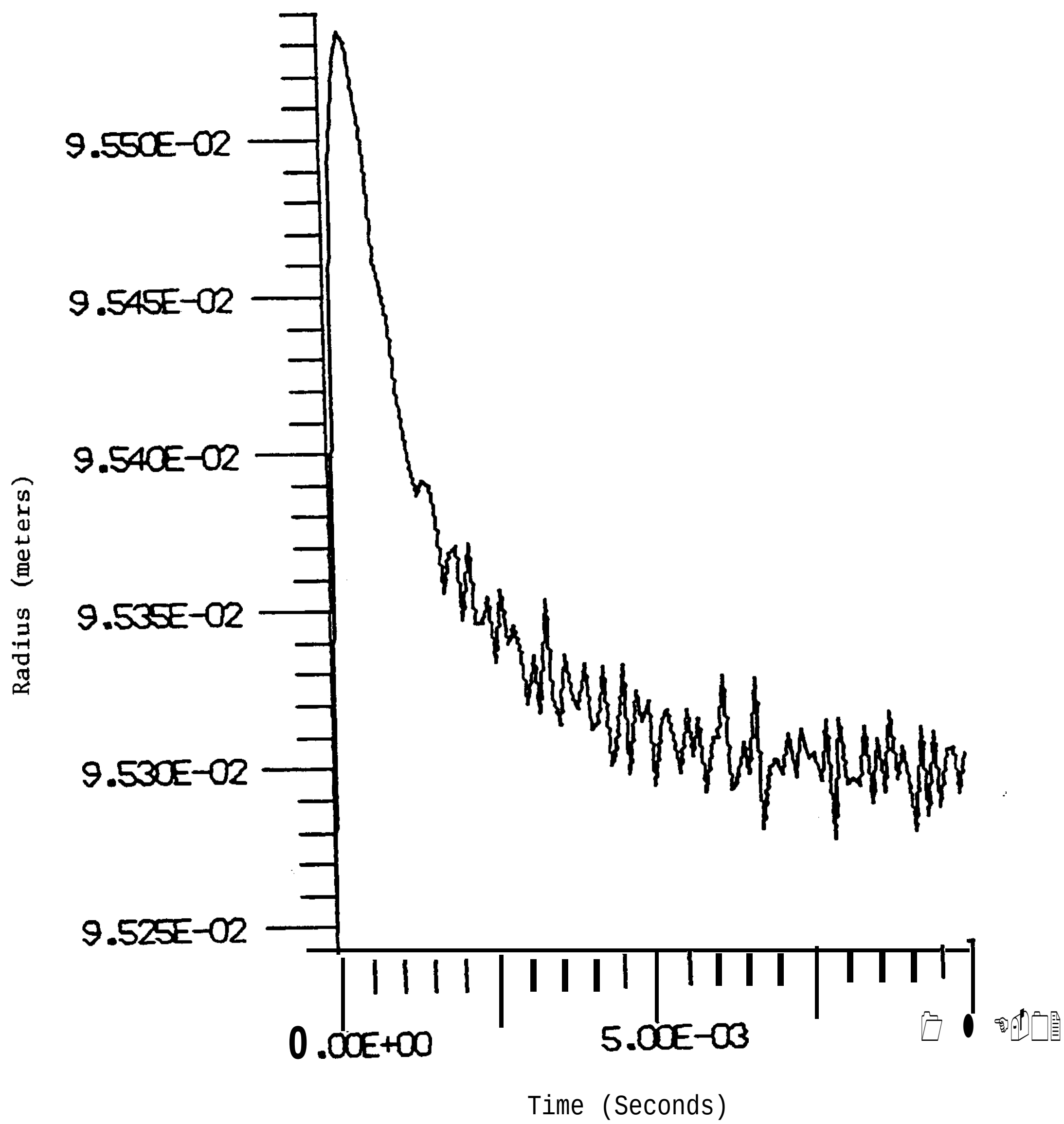


Figure 17. Case 3 - Wellbore Wall Radius-Time History

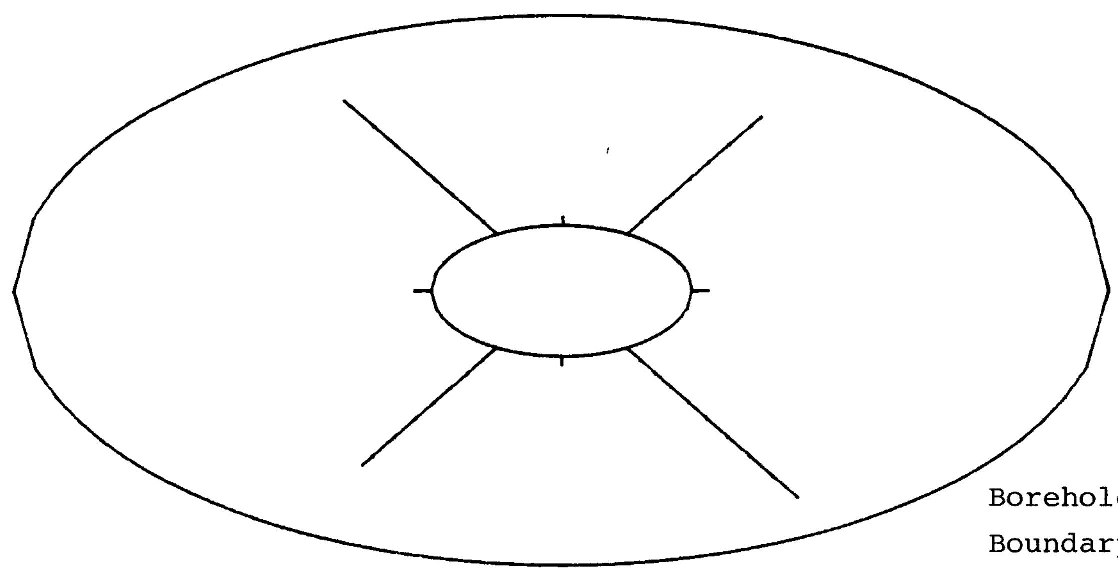


Figure 18. Case 3 – CAVS Fracture Plot at 10 Milliseconds
(No change after .5 Milliseconds)

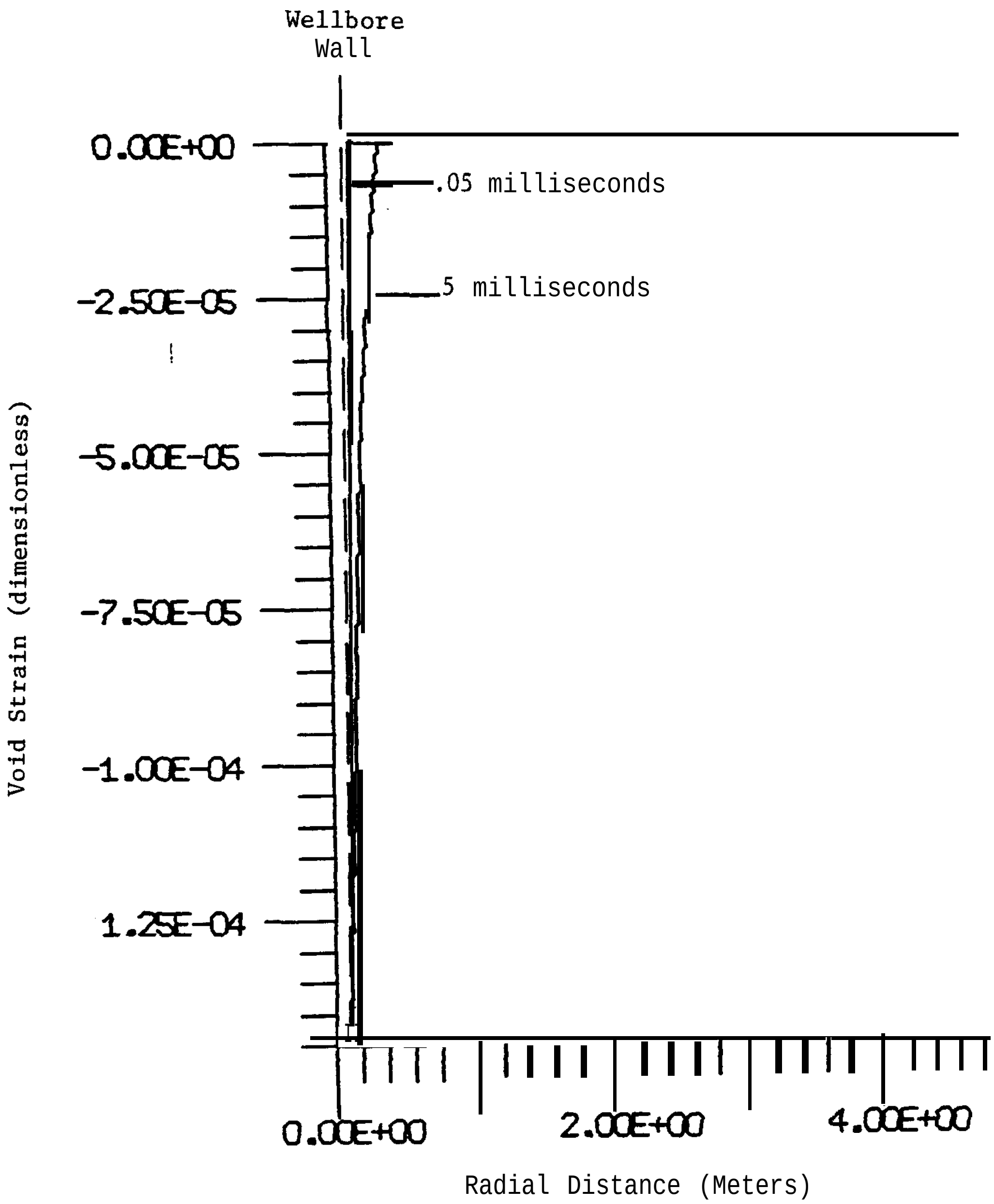


Figure 19. Case 3 - Crack Void Strain versus Radial Distance

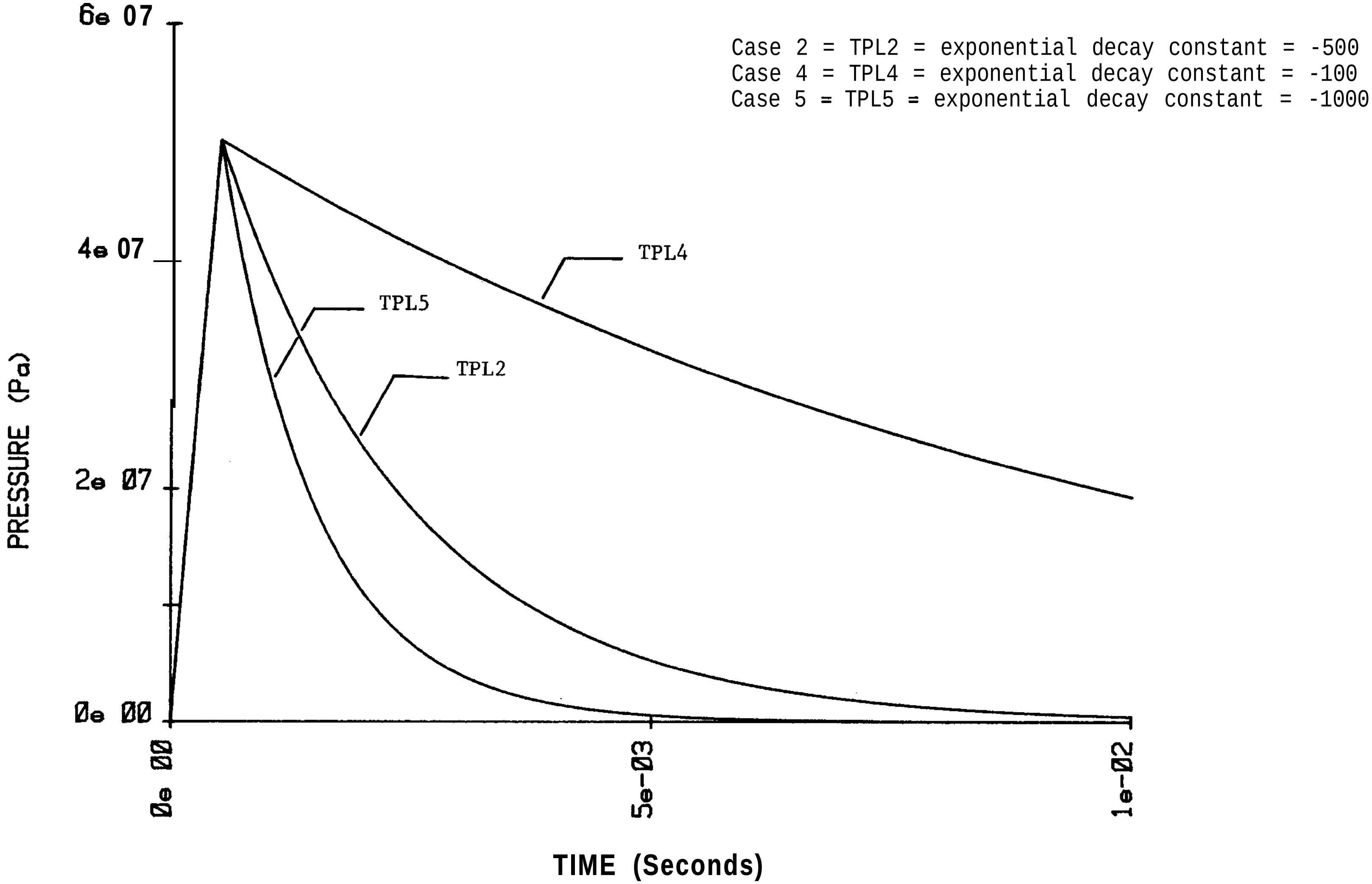
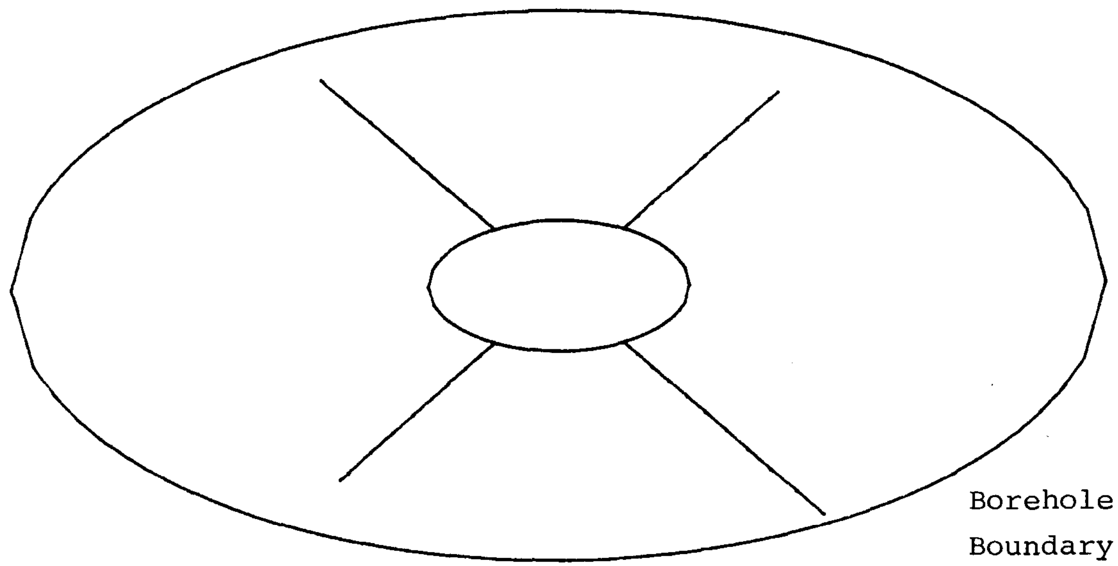


Figure 20. Group Two Pressure-Time Histories Applied at Wellbore Wall

File # 5, Index 9   TPL4: 1 0 0 GPa/s, - 1 0 0 decay, t= 2 ms



Borehole radius = 0.1 meters
Boundary radius = 0.4 meters

Figure 21. Case 4 - CAVS Fracture Plot at10 Milliseconds
(No change after 1 millisecond)

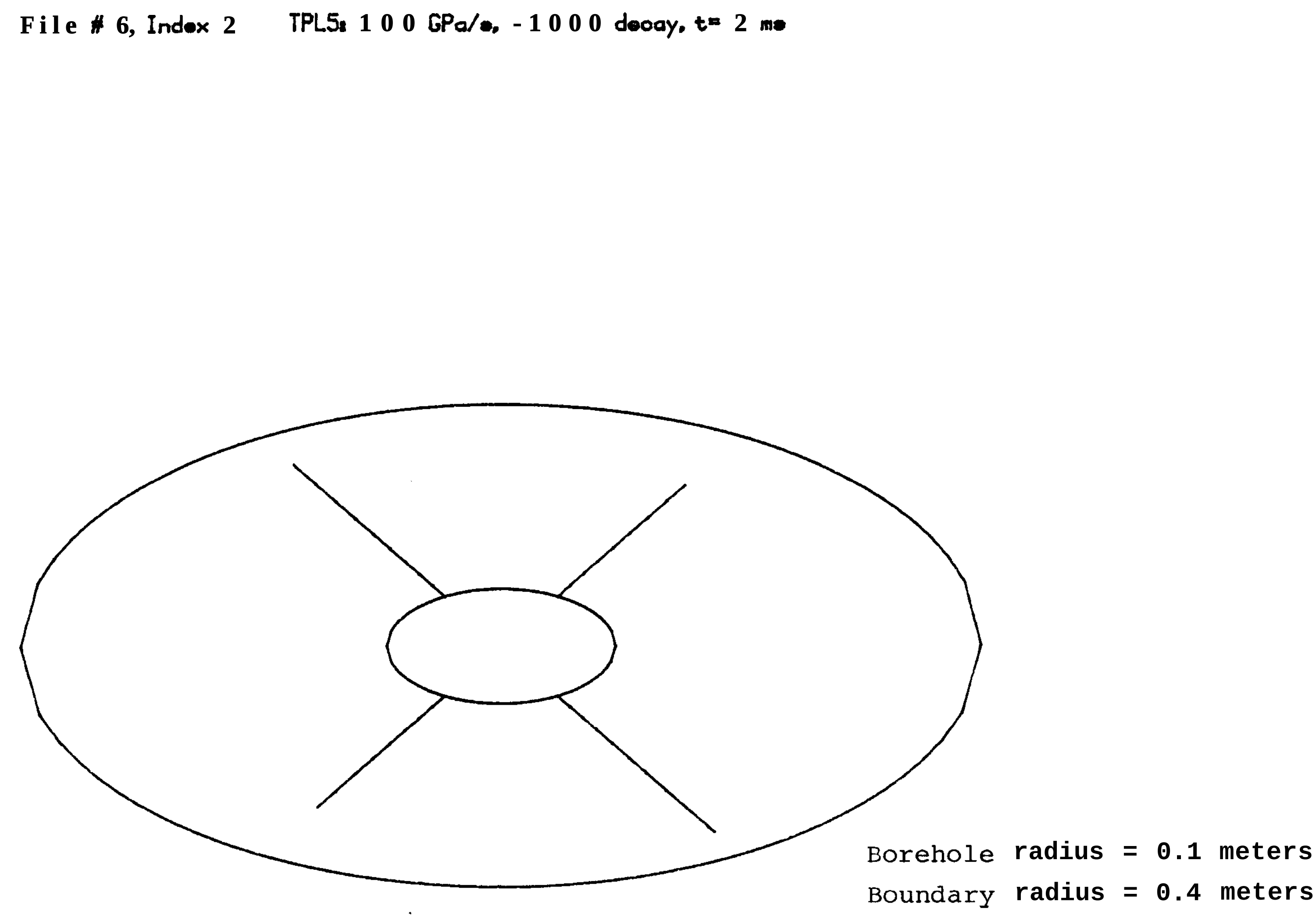


Figure 22. Case 5 - CAVS Fracture Plot at 10 Milliseconds
(No change after 1 millisecond)

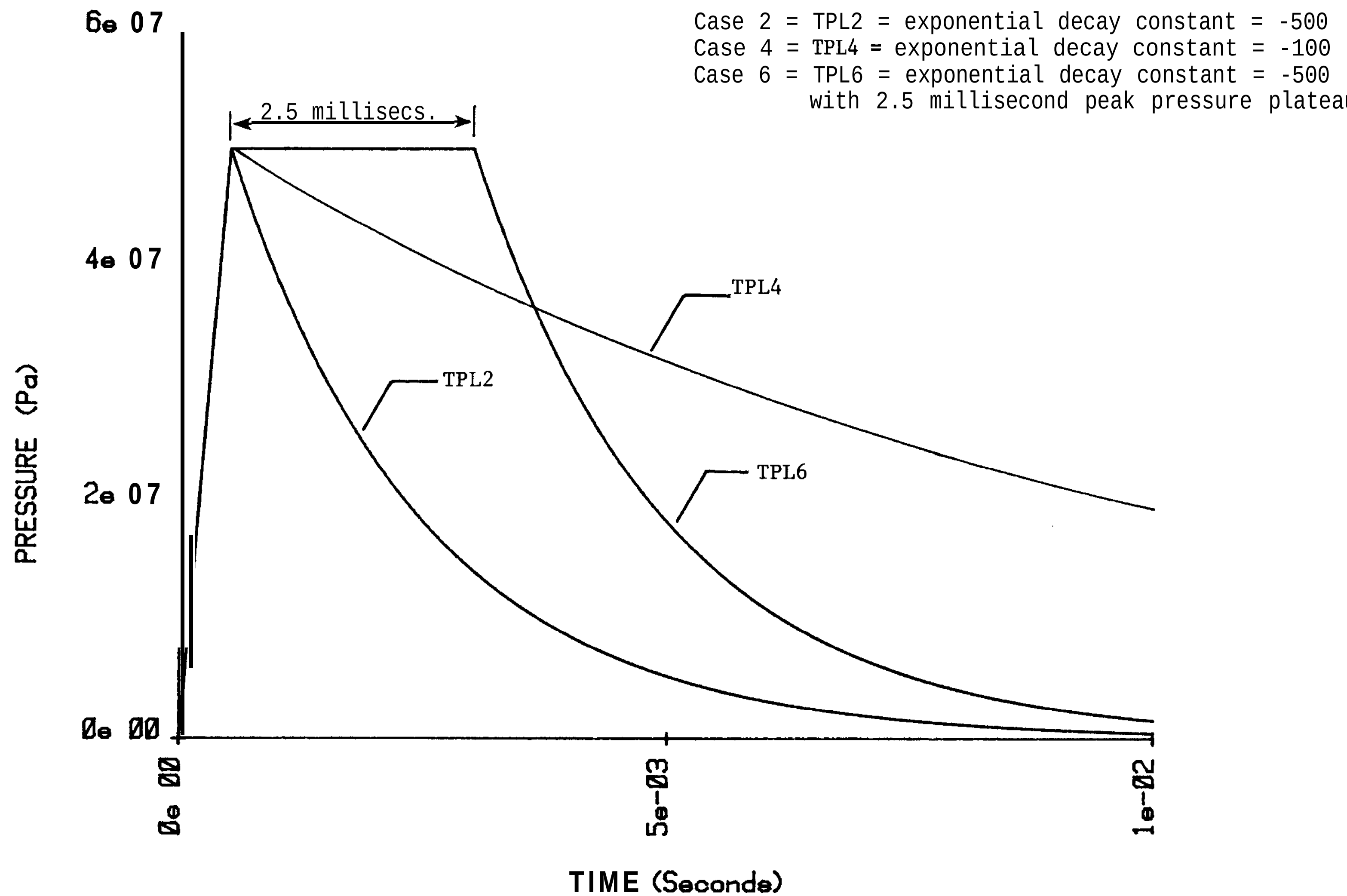
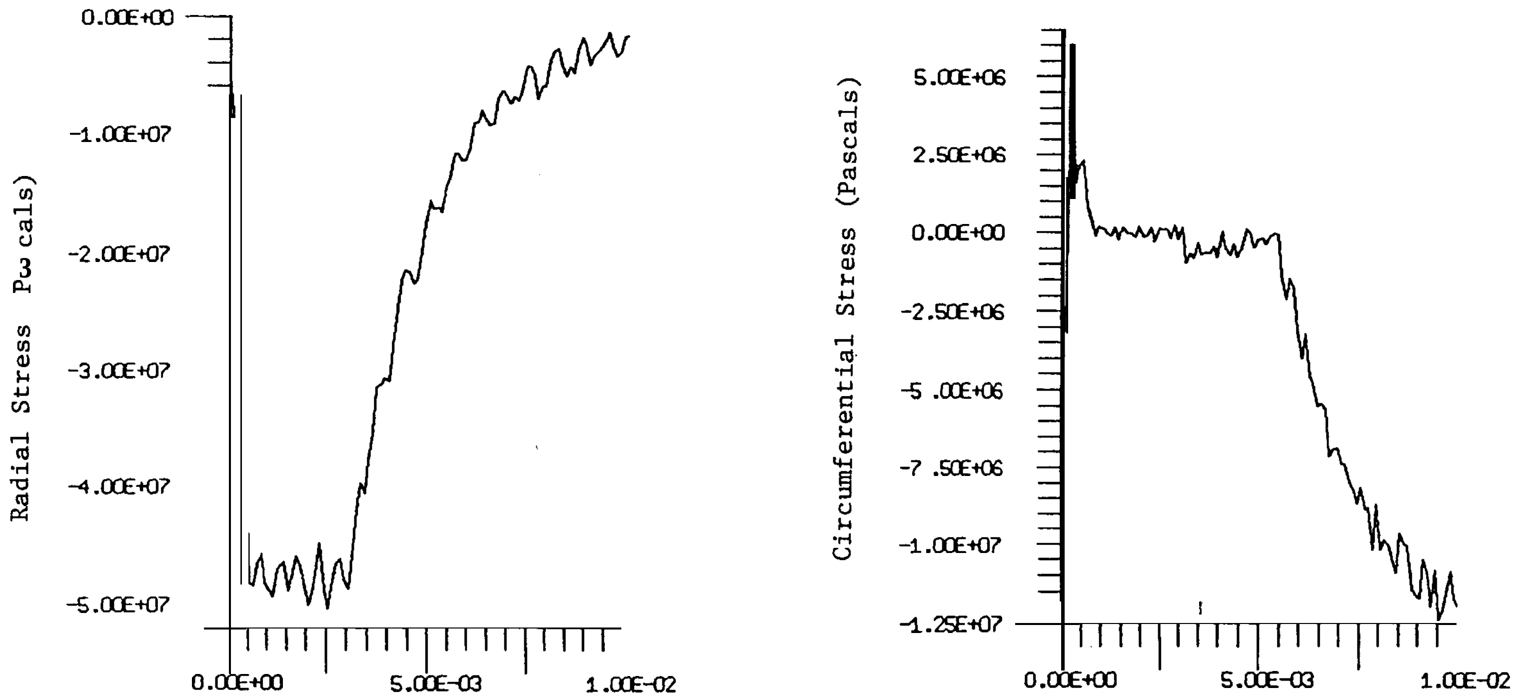


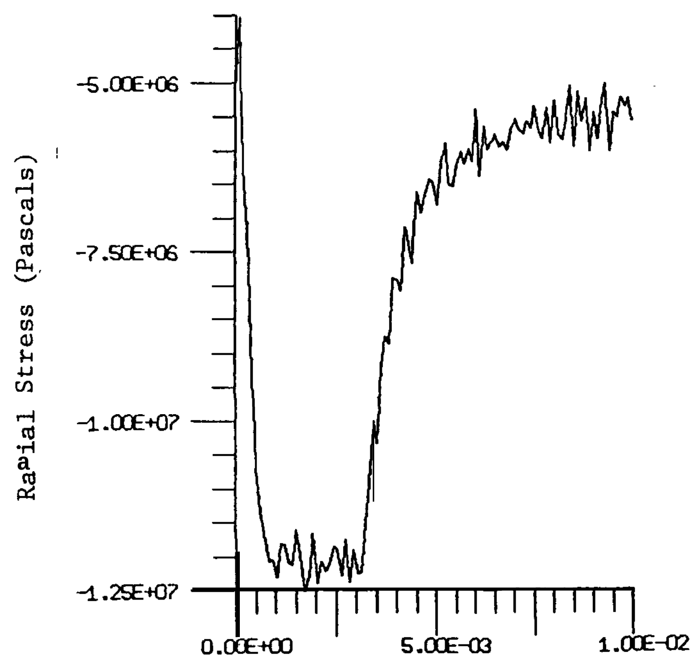
Figure 23. Group Three Pressure-Time Histories Applied at Wellbore Wall



Time (Seconds)
(a) Radial Stress

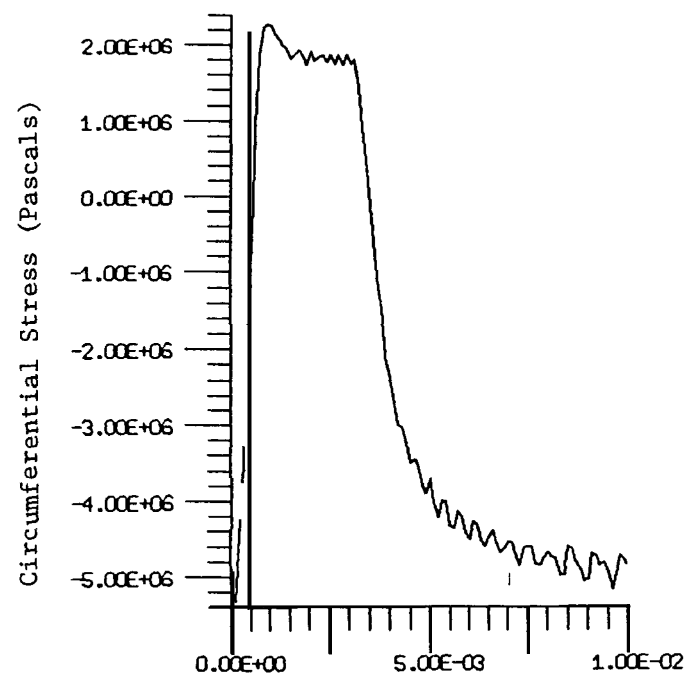
Time (Seconds)
(b) Circumferential Stress

Figure 24. Case 6 - Stress History in Shale Adjacent to Wellbore Wall



Time (Seconds)

(a) Radial Stress

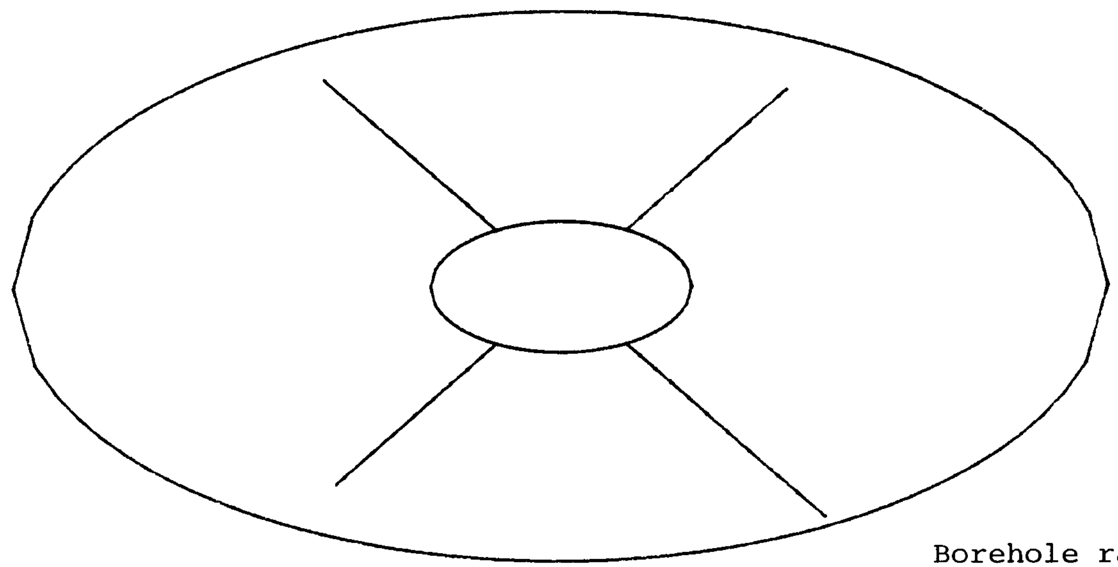


Time (Seconds)

(b) Circumferential Stress

Figure 25. Case 6 – Stress History in Shale Approximately 0.5 Meters from Wellbore Center

File # 6, Index 4 TPL6: 100 GPa/s, -500 decay, 2.5 ms plateau, t= 3 ms



Borehole radius = 0.1 meters

Boundary radius = 0.4 meters

Figure 26. Case 6 - CAVS Fracture Plot at 10 Milliseconds
(No change after 1 millisecond)